

Monitoring Morphology and Currents at the Hatteras Breach

By

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ABSTRACT

On 18 September 2003, Hatteras Island, North Carolina, was breached by Hurricane Isabel about 6 miles northeast of Hatteras Inlet to connect Pamlico Sound with the Atlantic Ocean. The breach occurred at a location of minimum island width and elevation. As part of research on coastal inlets, the new opening was surveyed to provide much-needed data on the hydrodynamic and morphologic evolution of barrier island breaches. Two topographic and shallow water surveys were conducted 10 days apart to capture short-term temporal changes in the breach morphology. Analysis of the survey data indicates rapid morphology change. Ebb and flood shoals formed within 2 weeks of the breach. The main breach channel widened by as much as 125 ft and migrated to the west by as much as 80 ft in the 10 days between surveys. Water levels on both the ocean and sound side of the barrier were also measured. Current velocities were measured with surface drifters and with an ADCP during two field deployments. Maximum current velocities were on the order of 7 ft/sec. The surveys provide quantitative data on the evolution of barrier island breaches that will be applied in development of numerical models of coastal breaching.

Additional Keywords: ADCP, barrier island, bathymetry, Hurricane Isabel, inlet, Pamlico Sound, survey

INTRODUCTION

Hurricane Isabel made landfall along the North Carolina Outer Banks on 18 September 2003. The eye came ashore between Cape Lookout and Ocracoke Island, near Drum Inlet. Isabel was a Category 2 storm on the Saffir-Simpson scale with maximum winds of approximately 100 mph and produced storm surges 6.5 to 8 ft above normal tide level near the point of landfall. The storm breached Hatteras Island about 6 miles northeast of Hatteras Inlet between the villages of Hatteras and Frisco (Figure 1). The Hatteras breach quickly widened to an overall width of over 1,500 ft. The breach contained two "breach islands" that created three distinct breach channels (Figure 2). During a 1933 storm, a breach occurred at nearly the same location. A bridge was being built over the new inlet in the 1930s, but the inlet closed naturally before the bridge was finished and construction was stopped. The U.S. Army Corps of Engineers (USACE), Wilmington District mechanically closed the breach created by Hurricane Isabel on 1 November 2003 (Wutkowski 2004).

This section of Hatteras Island is characterized by having medium-fine sand from the mean high water (MHW) line to 6 ft depths. The average significant wave height, as determined by the Wave Information Study (WIS) Level 3 for 10 years (1990-1999) at station 262, is 3.6 ft with a standard deviation of 2.3 ft. Mean wave period is 6 sec with a standard deviation of 2.4 sec,

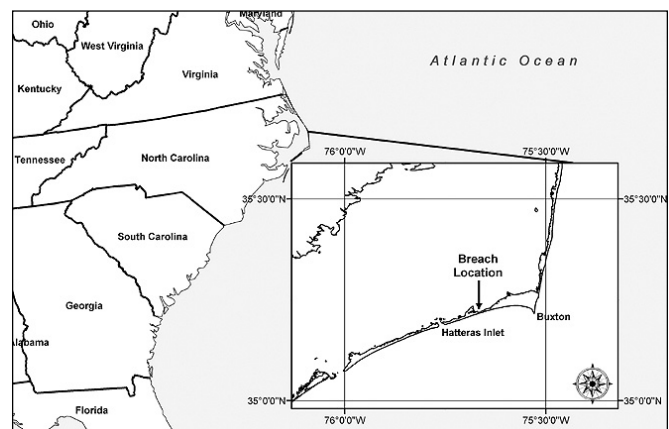


Figure 1. Location map for Hatteras breach.

and the predominant wave direction is from south to southeast. The mean tide range in this area, measured at the Cape Hatteras Fishing Pier, is 3.05 ft and spring tide range is 3.53 ft.

A coastal breach is a new opening in a narrow landmass such as a barrier island that allows water to flow between water bodies on either side of the barrier. Unintended breaches occur around the coast of the United States each year and are a serious concern in developed areas or areas of critical habitat (Kraus and



Figure 2. Hatteras breach, 22 September 2003 (USACE Wilmington District photograph).

Wamsley 2003). The Hatteras breach destroyed utility infrastructure and severed North Carolina Highway 12, isolating Hatteras Village from the rest of Hatteras Island. Parking lots and buildings near the breach were also destroyed. Highway 12 is the only transportation route east from the village. Residents were unable to drive to work and home. Businesses at Hatteras Village and on Ocracoke Island experienced loss of tourism revenue because of the restricted access.

Despite the potential societal and environmental costs associated with breaches, relatively little information is known on the physical processes of breaches. The Hatteras breach was in close proximity to the USACE Research and Development Center, Field Research Facility (FRF), which provided an opportunity to study large breaches of barrier islands. High-resolution surveys of the breach produced needed data on the hydrodynamic and morphologic evolution of barrier breaches. The surveys not only qualitatively describe the course of breach evolution, but also provide quantitative data for numerical models of coastal breaching under development by the USACE.

Two topographic and shallow water surveys were conducted to capture the short-term temporal changes in breach morphology. The first survey was conducted over 3-5 October 2003. A single multi-beam survey was conducted on 5 October. The second survey was conducted from 13-16 October. The bathymetry surveys of the breach channels, margin shoals, and flood shoal were performed with a Real-Time Kinematic (RTK) GPS Waverunner survey system. The system is designed for shallow water applications and can reach areas not accessible with more conventional survey methods. Topography was surveyed with an RTK-GPS system to clearly identify the shoreline of the beach and breach edge. The "breach islands" in the middle of the breach were also topographically surveyed to capture their slopes and shorelines. The multi-beam survey was performed to measure the size and extent of the ebb shoal. The multi-beam system also surveyed the main breach channel. Freeman, Bernstein, and Mitasova (2004) give a complete discussion of the survey plan and techniques.

During the first survey period, drogues were timed to approximate surface currents through the main breach channel. Drogue measurements were made at various times throughout the tidal cycle over 4-6 October 2003. The current was also measured with an Acoustic Doppler Current Profiler (ADCP) in the breach during two field deployments. The first current survey took place over 16-17 October near the time the second morphology survey was being conducted. The current was surveyed again on 24 October. Water levels were also recorded near the breach on both the Atlantic Ocean side and the Pamlico Sound side from 3 October to 12 November 2003. The purpose of this paper is to document the short-term morphologic evolution and hydrodynamic characteristics of the breach based on an analysis of the collected data.

OVERVIEW OF BREACHING PROCESS

Breaching potential is maximized if the barrier is low and narrow. Narrowing of the barrier results from shore erosion on either the ocean or bay/sound side. Lowering of the barrier results from dune degradation. Several causes of dune degradation can be identified, including fixed footpaths for beach access, seepage, undercutting and failure from wave attack, and wave overtopping. The narrowing and lowering of the barrier creates localized low profiles in the dune system. When water levels are elevated, inundation occurs and water begins to flow

through the localized low areas. Once the dune crest is submerged, erosion occurs rapidly and can be catastrophic.

After the complete wash out of the dune, a breach widens by erosion and collapse of the bank and deepens as flow scours the channel. Margin shoals are often formed immediately after breach opening. If the breach scour is sufficiently deep, water flow can occur between the two water bodies on each side of the barrier, even after the storm subsides. Tidal flow then continues to widen and deepen the breach channel. If the breach flow is strong enough to flush littoral drift-derived sediments from the breach faster than it is introduced, the breach is maintained and a tidal inlet formed. The flushing of sediment by the tidal current may create an ebb and/or flood shoal.

Hatteras Island was breached by elevated water levels and wave attack from the ocean side. The barrier is approximately 500 ft wide where the breach occurred, one of the narrowest sections along Hatteras Island. The long-term shoreline recession rate at this location is about 3 to 4 ft/year (Overton and Fisher 2004). Airborne LIDAR surveys by the U.S. Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) show that the breach occurred not only at a location of minimum island width, but also at a minimum of island elevation (Sallenger 2004). The primary cause of the low dune elevations is likely wave attack as a result of the receding shoreline. However, beach access may also have contributed. The breach occurred near a parking lot for beach goers. Dunes at access points are often lower due to foot traffic. If possible, coastal managers should discourage beach access at narrow regions of barrier islands and establish access points where the barrier island is wide.

The narrowing and lowering of Hatteras Island at this location weakened the barrier and subjected it to breaching. Evidence of powerful overtopping water flow was observed at the breach. Brush and other vegetation adjacent to the breach channels were matted and flattened toward the Pamlico Sound by overwhelming flow. Channelization at the lowest points in the barrier scoured the breach channels.

BREACH MORPHOLOGY AND SHORT-TERM EVOLUTION

The morphology and short-term evolution of the breach were examined through spatial surface analysis of three-dimensional digital elevation models (DEMs) created with high-resolution topographic and bathymetric data. Depths over the ebb shoal were collected on 5 October, in addition to the surveys of 3-5 October (Survey 1) and 13-16 October (Survey 2). Survey 2 had

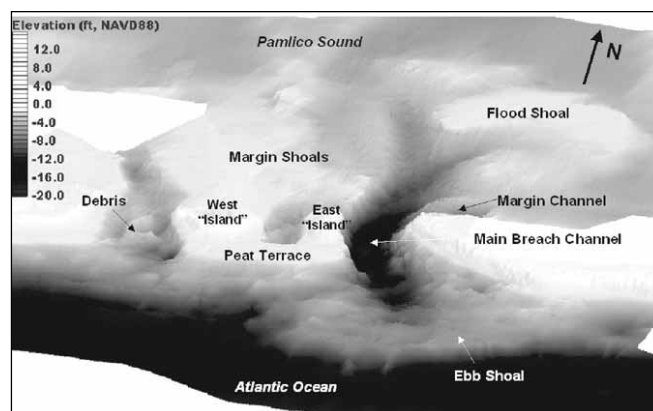


Figure 3. Digital elevation model of Hatteras Breach.



Figure 4. Western edge of peat terrace, looking southeast. The peat extends approximately 1.5 to 2 ft above the adjacent sandy bottom.



Figure 5. West breach channel, looking east, 5 October 2003. Note the old bridge pilings on the right and the extensive road debris in the channel.

best coverage of the nearshore region just seaward of the breach openings and, combined with the ebb shoal data, provides the most comprehensive data set. Figure 3 is a DEM created for illustrative purposes from Survey 2 data combined with the multi-beam ebb shoal data. Three breach channels, separated by breach islands, are well defined. The breach islands were not washed away because of resistance of peat outcroppings that fronted the islands on the ocean side (Figure 4). The peat acted as an erosion-resistant barrier, revetting the island at this location. The broad peat terrace extended from the eastern most breach island, across the middle breach channel and west breach island (Figure 3).

The peat terrace restricted flow in the middle breach channel, which was about 225 ft wide. Water flowed through the middle channel and over the peat terrace only at higher tide elevations. The restricted flow resulted in little scour of this channel. Maximum depths in the middle channel were about 5 ft NAVD88 (1988 North American Vertical Datum). The west channel was about 350 ft wide and littered with debris (Figure 5). Pilings from the bridge partially constructed in the 1930s extended across the channel on the ocean side. Large chunks of asphalt and roadbed material were visible at lower tide elevations, particularly on the west side of the channel. Near the center of the channel was a peat outcropping with large chunks of asphalt resting on top. The flow through the west channel was somewhat greater than that of the middle channel. Survey 2 maximum

depths in the west channel were 7 to 10 ft NAVD88. The eastern most breach channel was approximately 325 ft wide on the sound side and 350 ft wide on the ocean side and was the main channel as it captured a majority of the tidal prism. The unrestricted flow through this channel created scour depths down to 20 ft NAVD88.

The flood shoal is readily identifiable in Figure 3. The Survey 1 DEM showed that a flood shoal formed within 2 weeks after the breach opened with the centroid approximately 1,750 ft from Highway 12. The shallowest water over the flood shoal was less than 0.5 ft NAVD88 and had to be surveyed by wading, as depths were too small even for the waverunner system. The second survey showed little growth of the flood shoal. A volumetric analysis indicates that the flood shoal gained on the order of 10,000 cu yd of sand over the 10-day period. A well-defined ebb shoal also formed by 5 October (Figure 3). The ebb shoal extended offshore as far as 1,250 ft from the former location of the highway. Depths over the ebb shoal were 4 to 6 ft NAVD88. Waves were often observed breaking on the ebb shoal.

The DEM analysis indicates rapid morphology change. Figure 6 is a comparison plot of breach cross-sections from Surveys 1 and 2. Comparisons are made only where sufficient coverage of the channel was captured by both surveys. Due to debris and wave conditions, the seaward end of the west breach channel was not measured in Survey 1. As Figure 6 shows, there was little change in the west channel, because of the substantial amount of armoring by debris and peat. Flow velocities were significantly weaker than observed in the main channel. The sound end of the

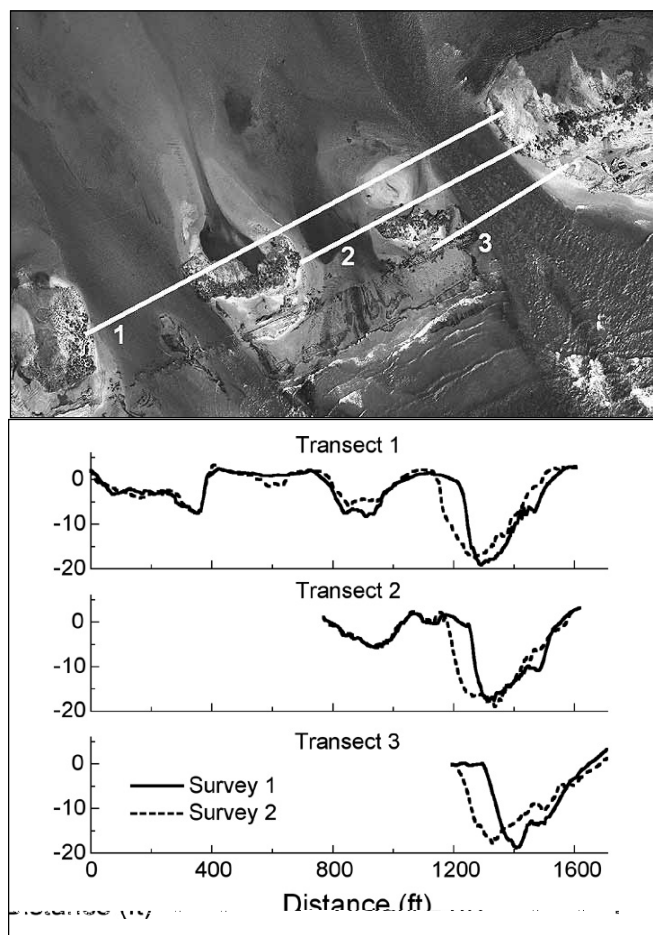


Figure 6. Comparison of Survey 1 and Survey 2 breach channel cross-sections (North Carolina Department of Transportation (NCDOT) photograph).

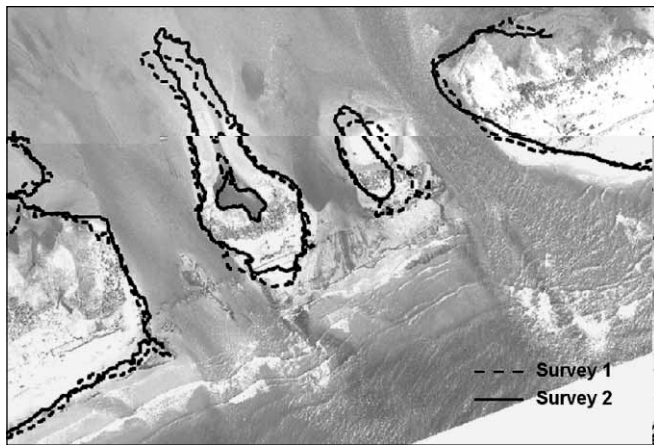


Figure 7. Comparison of the 0-contour (NAVD88). The aerial photograph was taken on 24 September, tide elevation -1.3 ft NAVD88 (NCDOT photograph).

middle channel shoaled approximately 2.5 ft in the 10 days between surveys. The sediment likely originated at the margin shoals on the sound side and could not be flushed out by flow restricted by the peat terrace. The central and seaward portions of the middle channel did not change between Surveys 1 and 2.

The main breach channel experienced the greatest amount of change. Defining breach width as the distance across the channel between the NAVD88 0-contour (which corresponds to +0.44 ft msl), the breach widened by approximately 125 ft on the ocean side, 65 ft through the middle part of the channel, and 25 ft on the sound side. From the center of the barrier toward the sound, the main channel migrated approximately 20 ft to the west over the 10-day period while on the ocean side the channel migrated over 80 ft to the west. The average channel depths were maintained and maximum channel depths generally increased through the middle part of the channel and decreased on the sound side over the 10-day period. The average cross-sectional area of the breach channel increased from 3,400 to 4,000 sq ft.

Figure 7 is a comparison of the 0-contour (NAVD88) between Surveys 1 and 2. The recession of both channel banks at the ocean end of the breach is evident. The east bank receded 25 to 45 ft while the west bank moved 40 to 80 ft. On the sound end of the breach channel, the east bank advanced approximately 25 ft, pushing the channel to the west. This end of the channel also continued to widen, however, as the west bank receded about 45 ft.

The prograding shoulder of the barrier island was supplied sediment from the ocean end of the breach bank and the sound side of the barrier island. A strong current was observed in the margin channel on the east side of the breach. Bank erosion was easily observed at this location. As the tide fell, a scarp formed on the sound side of the barrier. During lower tide elevations, the strong flow removed sand from the base of the scarp until a tension crack formed, leading to mass failure. The sandy bank material slumped into the margin channel, moving down the bank slope where the tidal current carried it downstream. At higher tide elevations, the scarp became submerged and was smoothed by the current flow and wave action. Recession of the 0-contour as a result of this process is seen in Figure 7. The maximum shoreline recession measured over the 10-day period at the margin channel was approximately 20 ft.

Figure 7 illustrates the elongation of the margin shoals behind both breach islands. The east island shoal advanced approximately 65 ft. The west island shoal migrated in a

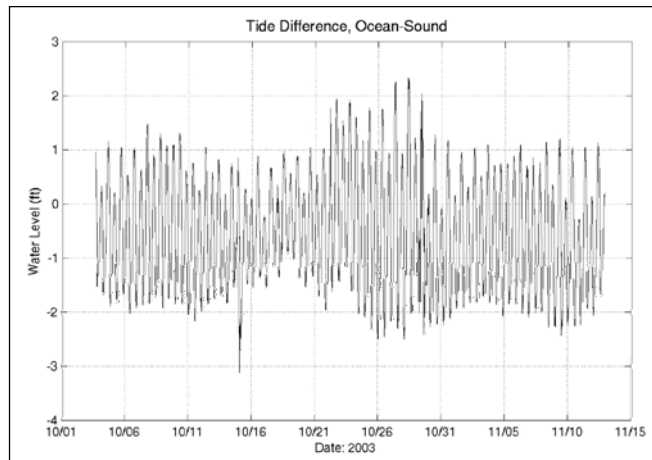


Figure 8. Pamlico Sound and ocean water level difference, 3 October to 12 November 2003.

northerly direction and also elongated by approximately 65 ft. The 0-contour on the front side of each island receded. This recession, however, was not from erosion of the peat terrace. The peat terrace elevation was below 0 NAVD88, and the sandy material on top eroded during higher tide elevations.

Figure 7 also shows beach shoreline change within about 500 ft of the breach. On the west side, the beach eroded approximately 35 ft. Sediment supplied by longshore transport advanced the shoreline to the east by as much as 55 ft within about 425 ft of the breach channel. The beach tended toward erosion at greater distances from the breach.

WATER LEVEL MEASUREMENTS

Water level differences between the sound and ocean drove the currents that maintained the breach. Two Seabird SBE-26 gauges were installed to measure water levels in the sound and ocean from 3 October to 12 November 2003. The sound gauge was deployed approximately 1,650 ft north-northeast of the breach in a water depth of 4 ft NAVD88. The sensor on the gage was at approximately 2.3 ft NAVD88. The ocean gauge was attached to a piling near the seaward end of the damaged Cape Hatteras Fishing Pier in Frisco, NC. The pier gage was 1.4 miles east-northeast of the breach where the nominal depth was 10 ft NAVD88, and the sensor was located at a depth of 5.6 ft NAVD88. The tide gauges sampled pressure at 4 Hz and recorded a mean value at 10-min intervals. Temperature and conductivity were also measured, from which salinity and density were computed. Water level was adjusted for variations in density. For shallow water, the corrections were small ($\sim \pm 0.03$ ft) compared to elevation differences ($\sim \pm 1.6$ ft).

The measured water level (head) difference between the ocean and sound are plotted in Figure 8. Water level head differences exceeding 2.3 ft were observed on both flood and ebb currents. Water levels for the pier, sound, and the head difference from 14-18 October are plotted in Figure 9 along with wind measurements from the Hatteras Weather Service (Mitchell Field, 2.5 miles east of the breach). Wind contributes to head difference, particularly in determining sound water levels. Pamlico Sound, having a large surface area and shallow water, can experience large wind-driven setup. On 15 October, the wind switched from having a west component to an easterly component, resulting in setup in the sound and a large negative head (ocean levels lower than the sound) of -3.1 ft. There was a gap in the wind data on 15 and 16 October, but based on measurements at the FRF (66 miles north of the breach), the

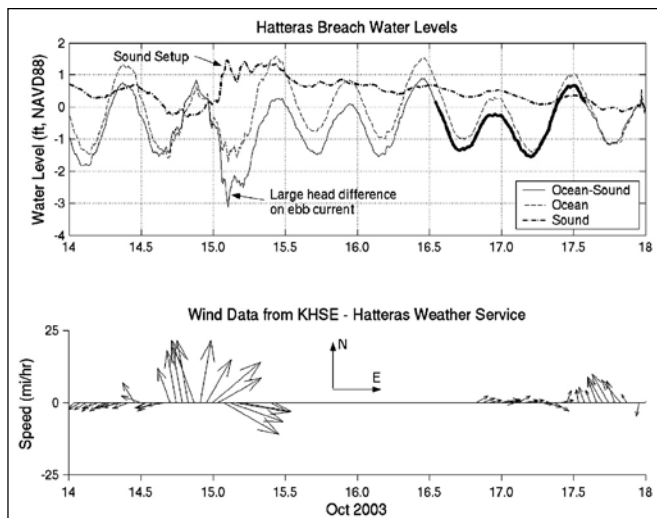


Figure 9. Ocean and sound water levels, head difference, and wind vectors. Bold line indicated times when bottom mounted ADCP was operational.

wind continued to be directed toward the east and south, favorable for setup in the southeast corner of the Pamlico Sound near the breach. As a result, a nearly continuous ebb current flowed for approximately 32 hours.

CURRENT MEASUREMENTS

The current through the main breach channel was estimated by timing surface drifters during Survey 1 and measured with an ADCP during two field deployments, the first of which coincided with Survey 2. Drogues were timed during the flood tide on 4 October and during ebb tide on 6 October. Surface current velocity was estimated from these measurements, as listed in Table 1.

The ADCP measurements were on 16, 17, and 24 October 2003. During the first deployment, a bottom-mounted ADCP

Day, Oct. 2003	Time (EDT)	Velocity (ft/sec)	Tide Stage
4	1247	1.6	Flood
4	1307	2.9	Flood
4	1340	4.9	Flood
4	1432	6.9	Flood
4	1514	7.2	Flood
4	1549	7.5	Flood
4	1707	5.2	Flood
4	1743	4.3	Flood
4	1836	~0	Slack
6	0808	3.9	Ebb
6	0847	4.6	Ebb
6	0919	5.9	Ebb
6	0955	6.2	Ebb
6	1022	6.2	Ebb
6	1053	5.9	Ebb
6	1149	5.6	Ebb
6	1233	4.9	Ebb
6	1307	4.6	Ebb

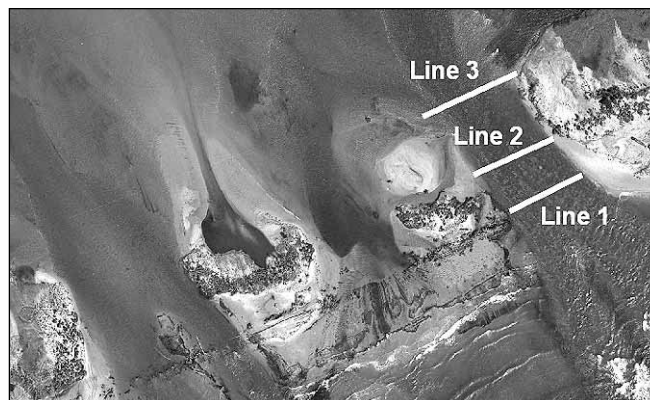


Figure 10. Approximate location of ADCP transects (NCDOT photograph).

was placed approximately midway along the channel where the surface currents appeared to be the strongest and where the channel was deepest according to previous bathymetric surveys. The ADCP was an RD Instruments (RDI) WorkHorse Monitor (1,200 kHz) and was fixed at a nominal depth of approximately 17 ft. The ADCP operated for 25 hr from 16 October 1300 EST to 17 October 1400 EST, 2003. Cross channel ADCP transects were also made from an instrumented Zodiac inflatable boat on 16-17, and 24 October. The ADCP employed for the transect measurements was also a 1,200 kHz WorkHorse Monitor. ADCP data were collected with RDI WinRiver software set to sample at 5 Hz but was only able to maintain approximately 2.5 Hz. The program was configured for 1.31 ft range bins and also acquired serial data outputs from an echosounder and RTK GPS unit. The echosounder (Knudsen 320B Echosounder) operated at 200 kHz and a nominal sound speed of 4,921 ft/sec, with sampling rate of 5 Hz. The roving GPS was a Trimble 4700 equipped with a Compact L1/L2 antenna. The base station was a Trimble 4000SSE. Surveys were Real-Time Kinematic (RTK) with approximately 0.07 ft accuracy in both the horizontal and vertical, while sampling GGA NEMA string output at 1 Hz. GPS coordinates were interpolated in post-processing to match the ADCP sampling rate. Echosounder data were sub-sampled by the WinRiver collection program because it only retains the most recent depth sample after the ADCP sample. The small mismatch in sampling times was not significant for this study.

Transect lines were chosen along three locations – approximately at the ocean end of the breach, near the middle, and on the sound side (Figure 10). The Zodiac crabbed (at an angle to the current) across the breach at a best attempt of constant speed, with each transect taking 2 to 3 min. Typically, two or three transects were made at each location before proceeding to the next line. Approximately 140 total transects were completed during both deployments. In addition, 12 current measurements were made using the boat as a drogue and currents computed from the recorded GPS time and position.

The current velocity was calculated by averaging measurements from the repeated transects at each location. A best-fit line was computed (least square linear sense) for each group of transects. Current velocity measurements were then averaged at 16.4 ft intervals along the computed transect line using measurements within 16.4 ft (horizontally) of the interval coordinate. Current velocities were not averaged vertically, maintaining the 1.31 ft vertical spacing.

An example of an averaged ADCP ebb current transect is shown in Figure 11 for Line 1 on 16 October. Strongest currents

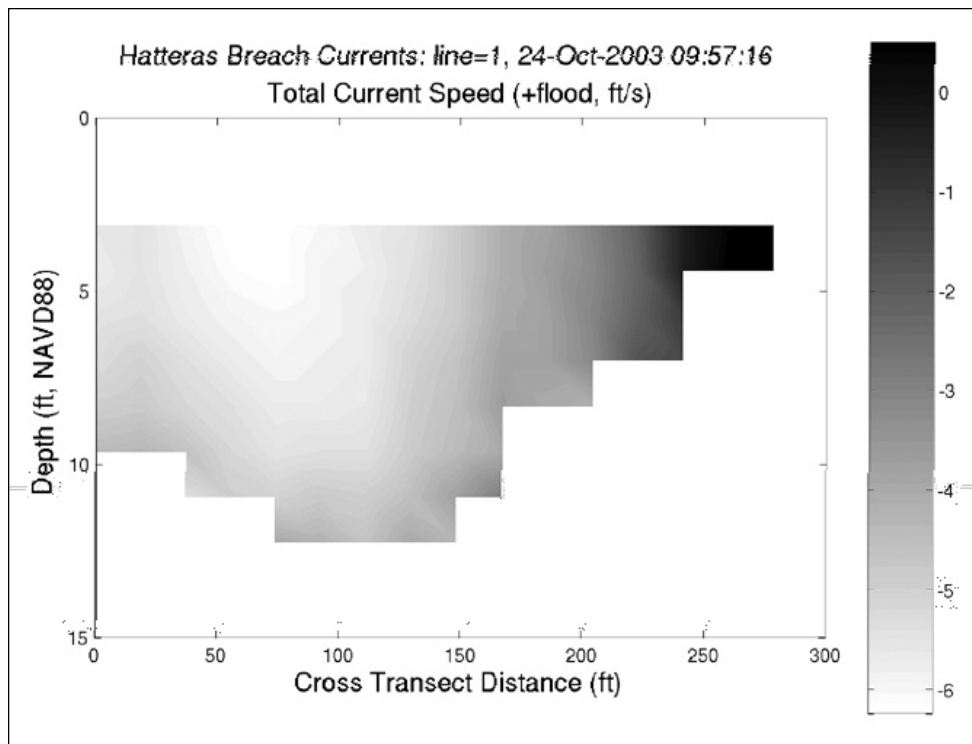


Figure 11. Example ADCP current transect at line 1.

are to the west (left) of the channel center. Ebb current transects for Line 2 indicate that the strongest currents tend towards the channel center. On Line 3, the strongest currents are observed to be east of the channel center and sometimes have two distinct maxima, one that parallels the main channel and another from the margin channel on the northeast side of the breach. This preliminary analysis of ADCP transect data corresponds to visual observations of surface currents, namely, that on ebb flow two distinct currents merged at the breach, and on flood flow there was a strong current through the main channel with a more diffuse current spread out over the area between the flood shoal and margin channel.

CONCLUSIONS

Hurricane Isabel breached Hatteras Island by a combination of elevated water level and wave attack from the Atlantic Ocean side about 6 miles northeast of Hatteras Inlet. The breach occurred at a location of minimum island width and elevation. As described in this paper, the breach was surveyed to provide data on the hydrodynamic and morphologic evolution of barrier island breaches.

Two combined topographic and shallow-water surveys were conducted 10 days apart to capture short-term temporal changes in the breach morphology. A flood shoal formed within 2 weeks after the breach occurred. A well-defined ebb shoal also formed during that period. Comparisons of the two surveys indicate rapid morphology change of the main breach channel. The main channel widened by as much as 125 ft and migrated to the west. Average channel depths were maintained and maximum depths increased through the middle part of the channel and decreased on the sound side over the 10-day period. On the west side of the

breach, the beach eroded approximately 35 ft. Sediment supplied by longshore transport advanced the shoreline east of the breach by as much as 55 ft within about 425 ft of the breach channel. The beach tended toward erosion at greater distances to the east.

Water level was measured on the ocean and sound side of the barrier. Current velocity through the main breach channel was estimated by timing surface drifters and measured with an ADCP during two field deployments. Maximum current velocity was on the order of 7 ft/sec. On the Pamlico Sound side of the breach channel, the strongest currents were located east of the channel centerline, tended to the center through the middle part of the channel, and were located west of the channel centerline on the ocean side. The ADCP data correspond to visual observations and surface drifter

estimates. A more thorough analysis of the current data is planned. The collected morphologic and current data will provide both qualitative and quantitative descriptions of breach evolution and will be applied in the development of numerical models of coastal breaching.

ACKNOWLEDGEMENTS

This study was performed under support provided by the Inlet Geomorphology and Channels Work Unit of the Coastal Inlets Research Program, U.S. Army Corps of Engineers (USACE). The authors thank Dr. Nicholas C. Kraus of the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, for his encouragement in this project and helpful review and John McCormick of the U.S. Army Engineer District, Wilmington, for his assistance in the field and office. Permission was granted by Headquarters, USACE to publish the information contained in this paper.

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